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THESIS

SHIP ROLL MODE INFORMATION
EXTRACTED FROM SEA TRIAL DATA

by

Mickie Kevin Wiser

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Thesis Advisor: Louis V. Schmidt

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Ship Roll Mode Information Extracted from Sea Trial Data

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ABSTRACT

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TABLE OF SYMBOLS

AVE	Average
[A]	Plant Matrix
[B]	Control Matrix
$[e^{At}]$	Transition matrix at time, t
est	Estimate
RMS	Root mean square, $E^{1/2}(y^2)$
t	Time, seconds
t_k	Time at "k-th" time sample, $\{k\} \cdot T_s$
T_n	Period of undamped system, $2\pi/\omega_n$, seconds
T_s	Sampling time, seconds
u(t)	Input function, continuous form
$u(t_k)$	Input function, discrete form
X	State vector, $[y\ \dot{y}]^T$
Y	Displacement variable, feet or radian
y_B	Second peak amplitude in RANDEC signature
y_s	Threshold value for RANDEC process
$[\Gamma(T_s)]$	Discrete system control matrix
ζ	Dimensionless damping ratio
$[\Phi(T_s)]$	Transition matrix $[e^{At}]$ at time $t=T_s$
ω_n	Undamped natural frequency, sec^{-1}

I. INTRODUCTION

The study of the motion of a ship at sea has long been a topic of interest to those associated with sea-going vessels. Of particular note is the fact that the roll motion of a vessel can be approximated by the use of a second order linear relation of the form,

$$\ddot{Y}(t) + 2\zeta\omega_n\dot{Y}(t) + \omega_n^2 Y(t) = u(t)$$

where ζ is the dimensionless damping ratio and ω_n is the undamped natural frequency. Hence, the knowledge of a system's modal frequency, as well as its damping are invaluable when determining the system's response behavior.

The purpose of the investigation was to identify the merits of the Random Decrement (RANDEC) procedure in extracting ship roll resonance modal damping and frequencies from ship roll angle time history data. Modal properties have been previously measured in calm water sea trials during subsidence in roll resulting from harmonic rudder excitation. The RANDEC method analyzes the roll time history during essentially fixed-rudder sea trials in which the excitation arose from ocean's hydrodynamic forces on the order of sea-state 5.

In 1987, DTNSRDC engineers were given access to a Spruance class destroyer for data gathering while the ship was underway during fleet exercises. During their time on board they collected information that resulted in a unique data base consisting of time histories of ship roll motion for this ship class. The availability of the data collected

allowed the application of techniques previously untried with respect to surface vessels. The process will help identify the ship system's modal damping and frequencies in the hope that the application of this knowledge may lead to an improvement in the seakeeping of Navy ships.

The Random Decrement Procedure (RANDEC) is a valuable method for extracting system traits from time histories that arise as a result of random system excitation. The approach was developed by Cole [Ref. 1]. The RANDEC procedure has been used extensively in aircraft design to determine modal properties from data obtained during wind-tunnel flutter tests [Ref. 2]. The only requirement of the method was that the excitation be random and of sufficient band width so that the wind tunnel model responded as a narrow band-pass filter. The process provides an alternate means of establishing the modal properties of a system response. As previously noted, this study is the first application of the RANDEC process to ship data, consequently the results on modal damping and frequencies will be unique.

In the RANDEC procedure segments of a random time history which start at a predetermined constant amplitude are collected, shifted and averaged to form a curve which is called the randec signature. Damping is obtained from the RANDEC output information in much the same way as from a free vibration decay. This is because the RANDEC output is representative of a free vibration decay curve in which the system is displaced to the same initial amplitude and released.

The RANDEC procedure involves the use of a given threshold value, y_s, to initiate the manipulation of the time history signal. As shown in Figure 1, the threshold value is

set and the time history signal checked for crossing points. Beginning with the crossover point and continuing for a predetermined period, the information that makes up the time history signal on that segment is recorded. The procedure is repeated for each subsequent crossover point that exists for the given threshold value and time history trace. Each of the data segments, known as time lagged data sets, is shifted to the ordinate axis and averaged to obtain a single output signal. The output signal is the representative RANDEC signature for the original time history.

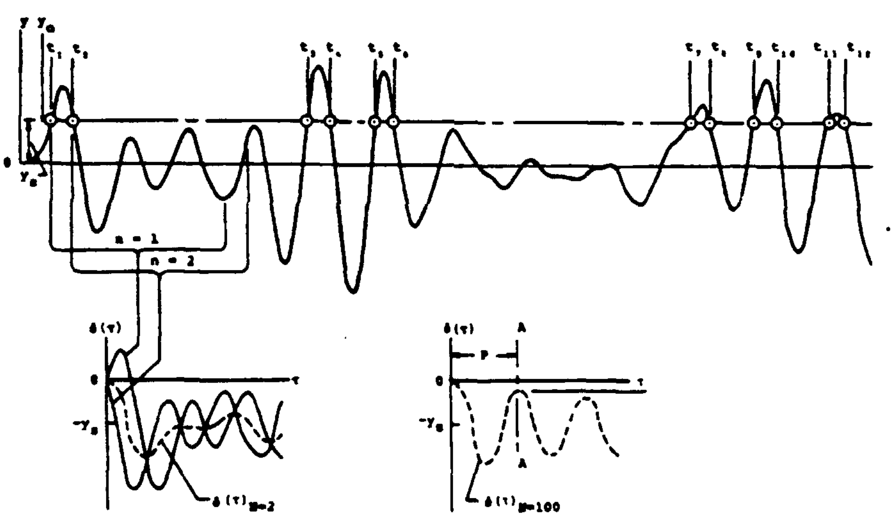

Figure 1. Development of a random decrement signature [Ref. 1].

There are a number of parameters that directly affect the outcome of the RANDEC procedure. The first of these is the threshold value, y_s. The threshold value is of critical

importance in that it directly affects the number of time-lagged data sets that are obtained during the data processing. It is obvious that the number of lagged data sets is inversely related to the magnitude of y_s. Furthermore, a larger number of segments available for averaging serves to increase the accuracy of the output signature. Cole recommended that the threshold value be maintained within approximately fifteen percent of the root mean square (RMS) of the time history signal.

The next point of consideration is the number of data points that should be contained in each of the time-lagged data sets. The number of points subsequent to crossover determines both the length and number of cycles contained in the RANDEC signal. As the end of a RANDEC signature was approached, the validity of the RANDEC response curve deteriorates due to a lack of information from the average of the time-lagged data. The larger the size of each of the time-lagged sets, the larger the size of the resulting RANDEC data group. However, as each data base contains a finite number of points the process is limited to the information available.

The final point of consideration is that of the number of time-lagged data sets available for averaging to form the RANDEC signature. As previously noted, the RANDEC process will yield greater accuracy with a larger number of lagged sets available for use. This point arises from the propensity of the impulse and random components of the forcing function to average to zero, leaving only the step response to be displayed in the RANDEC signature. Consequently, a higher number of lagged data sets should be obtained if possible.

II. DEVELOPMENT OF THE RANDOM DECREMENT ALGORITHM

Background information on the RANDEC process has been addressed above, so the scope of the present discussion will be limited to the development of the computer code designed to implement the procedure.

The code for the RANDEC program was created using a personal computer (PC) based software language - Microsoft's Quickbasic® [Appendix A]. The algorithm developed was a modified application of the stated RANDEC procedure because of the data base being in a digital form [Ref. 1].

The first objective of the program was to screen the time-history data for threshold crossing points. This was accomplished with a series of IF-THEN statements that determined crossover regardless of whether the curve had a local positive or local negative slope. If crossover were determined to have occurred, (i.e., $y = y_s$ when $t_k<t<t_{k+1}$), the logic program then went to a subroutine for determining the shift-fraction for the forthcoming data segment.

The shift-fraction was the means by which the digitally based data was reconciled to the technique that was designed for continuous sampling. Once crossover was determined to have taken place between two subsequent time points, (t_k and t_{k+1}), a linear interpolation was performed to determine the fraction of the distance between the points at which the threshold value was achieved. This fraction was then used to calculate the interpolated value between each of the following pairs of data points in the lagged data

set. Each of the interpolated data points was assigned an index and stored in a specified array for further operations.

Using the array to sum each of the time-lagged data sets made the task of averaging the segments a simpler and thus more efficient process. Initially, a two dimensional array was used to store each of the segments but was eliminated as the only concern was the final average of each of the indices for use as the RANDEC signature.

Initial test runs of the RANDEC algorithm showed that the signal was affected by the existence of a mean value other than zero in the time history data. Consequently, a subroutine was provided to remove the mean from the input data, as well as to calculate the RMS needed to set the threshold level for the RANDEC program. Ultimately, the output data was stored in user specified disk files, and the number of crossover points and data sets were printed to the computer screen.

Validation of the RANDEC algorithm was accomplished using a data set with known properties prior to employing the process on the actual ship data base. The control data group possessed properties very near to those of the ship data - both in dynamics and sampling times, as well as in data set length. The ship data sets were made up of data taken over a period of 20 minutes, sampled at a rate of 3 times per second, for a data run length of 3600 points.

III. PROGRAM VALIDATION

A. SHIP MODEL DEVELOPMENT

For the purpose of program validation, a second order system with dynamic properties similar to that of the Spruance class destroyer's roll resonance mode was used. The second order model was devised with the dynamic properties of ζ_s=0.08 and ω_n=0.40sec^{-1}, which approximate the roll resonance modal properties of the Spruance class destroyer [Ref. 3]. The state-space form,

$$\dot{\boldsymbol{X}} = \boldsymbol{A}\boldsymbol{X}+\boldsymbol{B}\boldsymbol{u}$$

with a solution of

$$\boldsymbol{X}(t) = e^{\boldsymbol{A}t}\boldsymbol{X}(0) + e^{\boldsymbol{A}t}\int_0^t e^{-\boldsymbol{A}\tau}\boldsymbol{B}\boldsymbol{u}(\tau)\,d\tau$$

was altered from the continuous to the discretized form using a sampling time of T_s = 0.3333 seconds in order to closely represent the actual ship data base. In the discrete form, the solution takes the form of a recursion relation, i.e.,

$$\boldsymbol{X}(t_{k+1}) = \boldsymbol{\Phi}(T_s)\boldsymbol{X}(t_k) + \boldsymbol{\Gamma}(T_s)\boldsymbol{u}(t_k)$$

where

$$\boldsymbol{\Phi}(T_s) = e^{\boldsymbol{A}T_s}$$

and

$$\boldsymbol{\Gamma}(T_s) = [e^{\boldsymbol{A}T_s} - \boldsymbol{I}]\boldsymbol{A}^{-1}\boldsymbol{B}$$

Using the anticipated values of $\zeta = 0.08$ and $\omega_n = 0.4$ sec^{-1} resulted in the following matrices:

$$\boldsymbol{A} = \begin{bmatrix} 1.0 & 0.00 \\ -0.16 & -0.0640 \end{bmatrix} \qquad \boldsymbol{B} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\boldsymbol{\Phi} = \begin{bmatrix} 0.9912 & 0.3288 \\ -0.0526 & 0.9702 \end{bmatrix} \qquad \boldsymbol{\Gamma} = \begin{bmatrix} 0.0551 \\ 0.3288 \end{bmatrix}$$

For an in depth discussion of the state-space method, the reader is referred to Ogata. [Ref. 4:p. 741]

The validation process will yield an exponential decay envelope and a characteristic period. The relative agreement between the RANDEC procedure and the known dynamics of the reference second-order system will give an indication that a) the numerical algorithm was functional and b) the RANDEC concept yielded consistent results.

B. CONTROL GROUP DATA GENERATION

A random function generator was developed using the Monte Carlo approach to produce data similar in nature to that contained in the ship data base [Ref. 5:p. 67]. The results of the function generator were taken as the input to the state equation previously discussed and resulted in the formation of random second order system response signals.

As with the RANDEC algorithm, the random function generator was written using MS-Quickbasic® [Appendix B].

C. VALIDATION DATA RUNS

Validation of the RANDEC algorithm was accomplished using a random noise generator to form discrete time data groups of various lengths. The second-order system was excited by the random input data and a faired plot of the discrete data output had the appearance of a narrow-band filter when excited by broad-band noise as shown in Figure 2. The data lengths ranged from 4000 to 15000 points. For each set, the RMS value and mean were calculated and recorded. Runs were made for each data set with dissimilar threshold values. The threshold value, y_s, was varied between 0.7 to 1.2 times the RMS, where the RMS corresponded to the data set under consideration.

- Run 1. Made use of 4000 data points to establish a baseline for the RANDEC code in the range of the actual number of data points available in the ship's information.
- Run 2. Consisted of 4000 points as a repeat so that further insight might be gained in the results for the same length data as the ship data.
- Run 3. Saw the number of data points increased to observe the effects of increasing the time-history length. In this case, the data group consisted of 6000 points with an RMS value of 4.04278 and a mean of -0.00225.
- Run 4. Expanded the data to 8000 points. All RANDEC processing was repeated with an RMS value of 3.75291.
- Run 5. The data group was further expanded to 10000 points. RMS value for this set was 3.97792, with a mean of 0.0.
- Run 6. The data set was expanded to 15000 points. RMS for this group was 3.754. The mean value was again zero. Figure 3 and Figure 4 show the results of processing the time history data at threshold levels equal to data 1.0 and 1.2 times

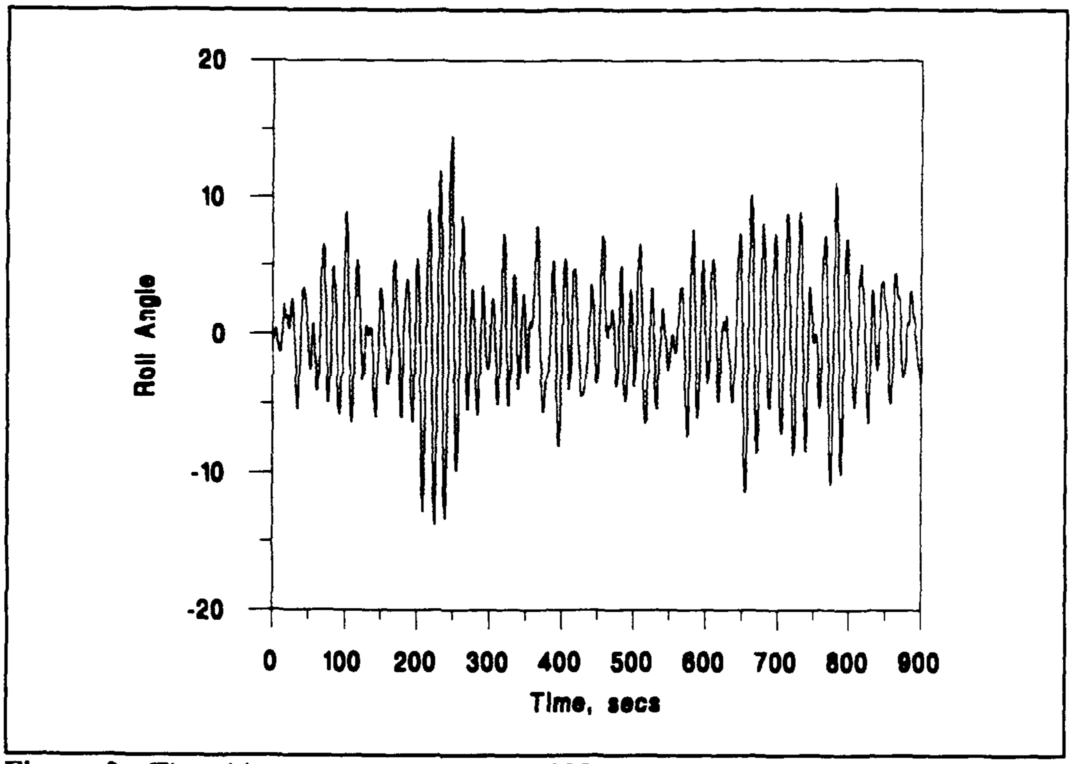

Figure 2. Time history segment from 15000 data point set.

RMS, respectively. Each of these figures show the resulting RANDEC signature, as well as the damping envelope for the assumed model using $e^{-\zeta\omega t}$ based upon ω_n=0.08 and ζ=0.08.

D. DISCUSSION OF VALIDATION RESULTS

In Tables I and II, y_s and y_B are the amplitudes of the first and second peaks from the RANDEC signature, respectively. Note also that the value of the first peak is that of the threshold setting for the run. The values of amplitude were used in the logarithmic decrement calculation of ζ_{est} using the equation $\zeta_{est} = 1/2\pi \ln\{y_s/y_B\}$. The roll period, T_n, was taken between the peaks giving y_s and y_B, and used to determine the natural

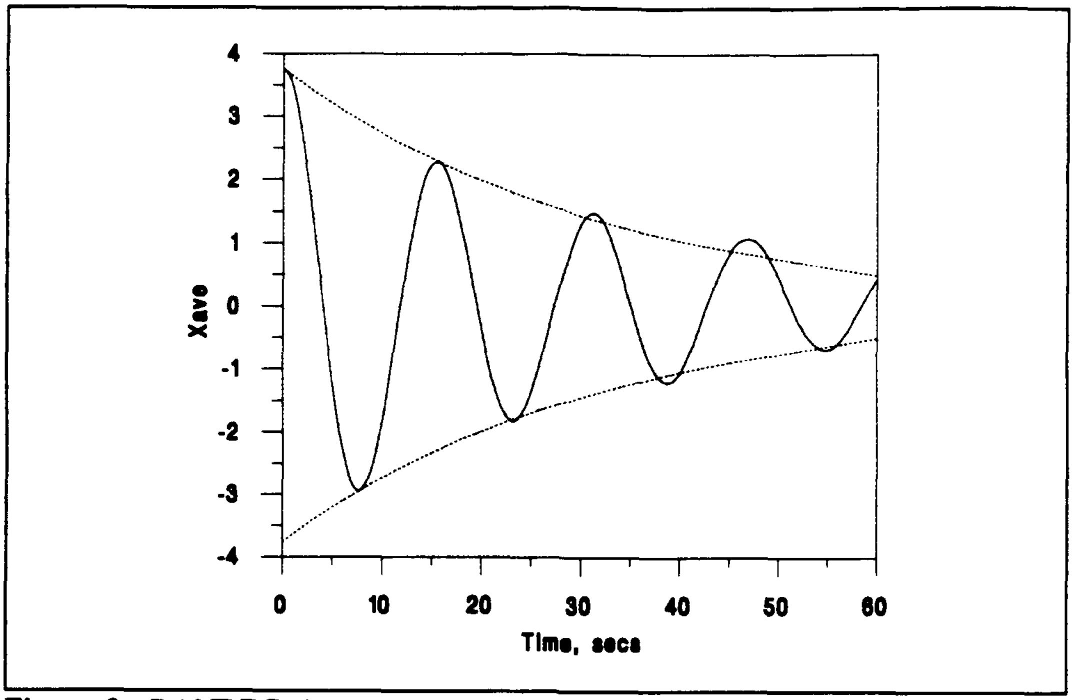

Figure 3. RANDEC signature, y_s=RMS.

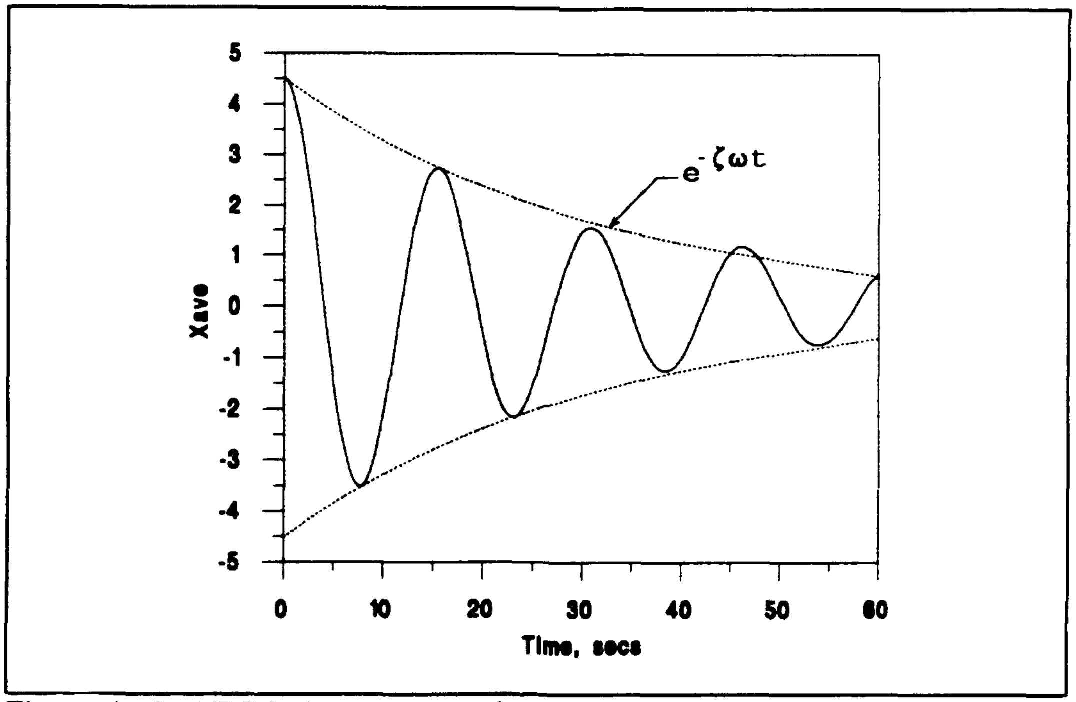

Figure 4. RANDEC signature, y_s=1.2 RMS.

TABLE I. VALIDATION RESULTS FOR VARIOUS SIZES OF DATA.

{%RMS}	y_s	y_B	Period, secs	ω_n, (sec^{-1})	ζ_{est}	#LAG SETS
RUN 1 (4000 points)						
70	2.688	1.558	16.33	0.385	0.0868	112
80	3.072	1.743	16.67	0.377	0.0902	110
90	3.456	2.053	17.0	0.370	0.0829	102
100	3.840	2.131	16.33	0.385	0.0937	92
110	4.224	2.581	16.33	0.385	0.0784	74
120	4.608	2.876	16.33	0.385	0.0750	70
RUN 2 (4000 points)						
70	2.665	1.720	15.67	0.401	0.0697	112
80	30.45	1.984	15.67	0.401	0.0682	110
90	3.426	2.078	15.67	0.401	0.0796	102
100	3.807	2.224	15.67	0.401	0.0856	96
110	4.187	2.226	15.67	0.401	0.1006	88
120	4.568	2.351	15.33	0.410	0.1057	80
RUN 3 (6000 points)						
70	2.792	2.014	15.66	0.401	0.0520	179
80	3.191	2.429	15.66	0.401	0.0434	161
90	3.590	2.532	15.66	0.401	0.0556	143
100	3.989	2.643	15.33	0.410	0.0605	127
110	4.388	2.890	15.33	0.410	0.0665	123
120	4.787	2.976	15.67	0.401	0.0757	102

TABLE II. VALIDATION RESULTS.

{%RMS}	y_s	y_B	Period, (secs)	ω_{est}, (sec^{-1})	ζ_{est}	#LAG SETS
RUN 4 (8000 points)						
70	2.822	1.875	16.33	0.385	0.0651	260
80	3.226	1.976	16.33	0.385	0.0780	236
90	3.629	2.274	16.00	0.393	0.0744	224
100	4.032	2.500	16.00	0.393	0.0761	194
110	4.435	2.844	15.67	0.401	0.0707	180
120	4.838	3.062	15.67	0.401	0.0728	162
RUN 5 (10000 points)						
70	2.785	1.588	16.00	0.393	0.0894	310
80	3.182	1.775	16.00	0.393	0.0929	290
90	3.580	2.000	16.00	0.393	0.0927	268
100	3.978	2.332	15.67	0.401	0.0850	242
110	4.376	2.650	16.00	0.393	0.0798	220
120	4.774	2.968	16.00	0.393	0.0756	204
RUN 6 (15000 points)						
70	2.628	1.715	15.33	0.410	0.0679	505
80	3.003	1.837	15.33	0.410	0.0782	461
90	3.379	2.104	15.33	0.410	0.0754	431
100	3.754	2.277	15.33	0.410	0.0796	391
110	4.129	2.500	15.33	0.410	0.0799	339
120	4.505	2.743	15.33	0.410	0.0790	321

frequency, ω_n. Finally, the number of time lagged data sets obtained for the threshold value are also shown.

Consideration of the values from Table I brings out a number of items concerning the results of the RANDEC algorithm for the control group data. First, note the strong influence of the threshold value, y_s, on the resulting properties obtained from the algorithm. In the validation process y_s was set at percentages of the data RMS value, which was previously calculated. y_s values for each data set ranged from 70 percent to 120 percent of the RMS. At the lower values of y_s, (i.e., 70 to 80 percent of RMS), the number of lagged data sets is increased above those runs with higher levels of threshold setting. It might be inferred that having a lower y_s value, which acts to increase the number of time-lagged data sets, would result in an improved RANDEC signature. However, the results of the validation process were to the contrary with a possible heuristic reason being that the lower threshold values do not allow the averaging process to pull-out the step response from the random generated impulse responses.

Each of the data runs, regardless of record length, showed that the RANDEC signature was most representative of the model's dynamic behavior when the threshold, y_s, was in the neighborhood of the time-history's RMS value. In particular note runs 2 and 6 from Table I and Table II, with 4000 and 15000 data elements, respectively. For both runs the greater accuracy is achieved for y_s in the range of 0.9 to 1.1 times the RMS. Figure 5 shows the effects of y_s upon the estimated damping level for each run. Note that for each run the values of ζ_{est} are relatively constant and there is a convergence of the data to ζ_{est}=0.08 in the proximity of y_s = RMS. In addition to improved damping estimates

in this y_s range, the estimated frequency values are also the more precise for each of the runs. Runs 2 and 6 show the estimated values for the RANDEC signature period and frequency have the greatest accuracy with the threshold set between 0.9 to 1.1 times the RMS. As previously discussed, the control group was designed with the properties of ζ=0.08, and ω_n=0.40 sec^{-1} (T_n=15.71 secs).

Next the effect of varying the length of the time-history data sets was considered. The data sets ranged in sample lengths from 4000 data points, close to the size of the ship time histories, to 15000 points. As expected, the more extensive data sets produced a larger number of lagged data sets for averaging and therefore yielded results that more closely approximated the expected system properties.

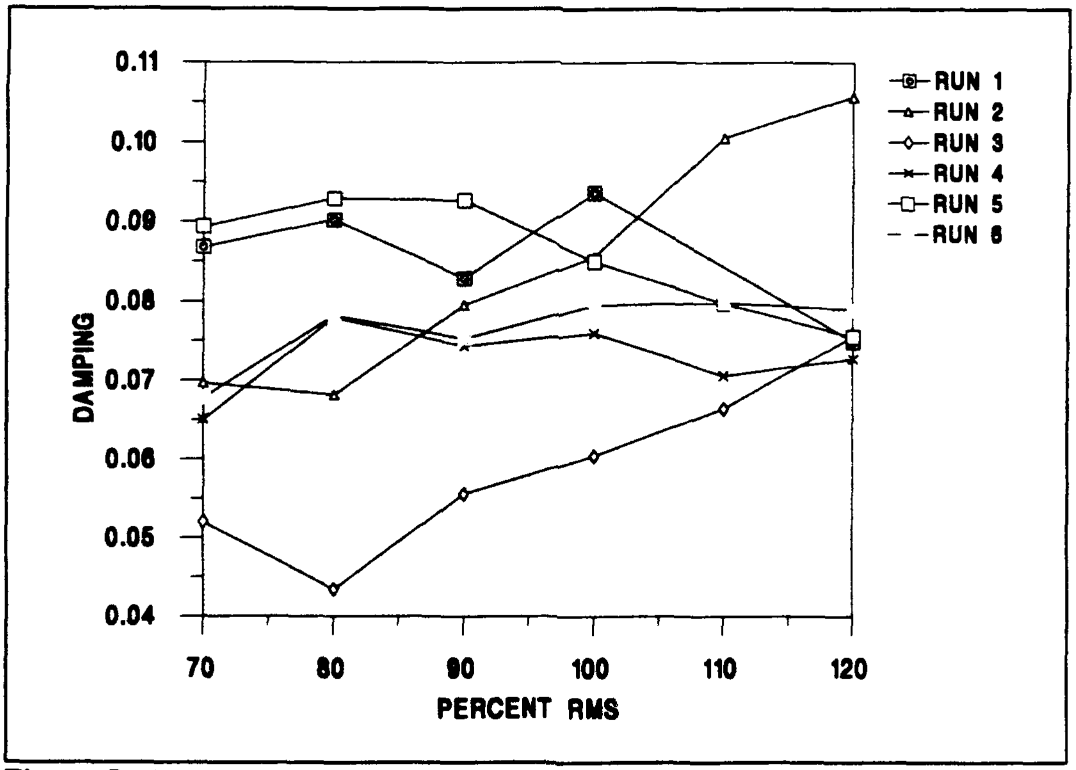

Figure 5. Damping versus y_s as a function of RMS.

Returning once again to Table I and Table II, runs 2 and 6 confirm the expectation of greater accuracy for the larger data sets. Consider, for example, the y_s=RMS results for the two runs. For run 2 with 4000 points, ζ_{est}=0.0856, and for run 6 with 15000 points, ζ_{est}=0.0796. The effect of record length upon the accuracy of ζ_{est} was approximately ±0.005. The longer time history traces contain more statistical information and consequently yield more reliable estimates. Since the actual ship roll time history data consisted of 3600 points per set, a slight degradation in corresponding accuracy of the RANDEC signature could be expected with the use of the ship data.

Another point is the large difference in the number of time lagged data sets. With the threshold set to the RMS value for each operation, run 2 produced only 96 lagged sets, while run 6 gave 391. It is clear that longer time history traces are preferred because of the more accurate results produced.

A smaller time history data set also reduces the number of elements that can be included in each time lagged set. Consequently the length of the resulting RANDEC signature (i.e., the number of cycles) that is valid for data extrapolation is reduced. Progressive deterioration of the signature past the first one or two oscillation periods may be attributed to a lack of statistical information because of the length of the original time history. As a result, when considering the ship test data, the use of the log-decrement procedure to calculate the ζ_{est}, and the number of cycles used to observe the ω_n were based only upon the first one or two periods.

Also note that with regard to time history data length, the number of resulting time lagged sets available most directly affects the accuracy of the RANDEC procedure.

Although it is possible to reach a higher number of threshold crossings by reducing the y_s, the results are much less precise than by increasing the sample length. Cole stated that in order to achieve satisfactory results, it was necessary to set algorithm parameters to obtain 500 lagged data segments. In the validation process this was achieved for the 70 percent threshold level of Run 6 with 15000 data points. Returning for a moment to Figure 5, the damping achieved for the 70 percent level was the least accurate for this run. Once again the tradeoff of the higher number of data segments versus the greater accuracy of the results with y_s near the data RMS value arises as a concern. It would seem that the higher degree of accuracy is obtained with y_s set at the RMS value, albeit with a lesser number of data segments.

Another means by which the number of data sets may be increased in each of the segments is to increase the length of the time history plot. This point is addressed again solely for the purpose of arguing the limitations of access to obtaining this information. The data sampling rate on the ship sea trials was three times per second, and by assuming ideally that a minimum of 15000 points would be necessary, that would equate to roughly one and a half hours of data gathering. As such, to record the data it would be necessary to maintain course and speed of the vessel for this period. This requirement of time is unrealistic as all data gathering on board operational naval vessels was on a "non-interference" basis; that is to say, the technical crew may not adversely affect the operations of the unit with regard to its tasking. Accordingly, there is a practical limit on the length of continuous data available for analysis.

IV. APPLICATION TO SHIP DATA

A. SHIP DATA BACKGROUND INFORMATION

The ship time histories included an extensive series of data runs that were collected over a variety of environmental and operational conditions. The environmental factors included wave height, wave direction, wind speed, and wind direction. Operational factors were primarily ship's speed and heading, with particular attention being paid to the use of the ship's rudder. The two groups of factors influenced the time response of the ship to the random input of the ocean's hydrodynamic forces [Ref. 6]. To reduce the influence of these factors, time history traces were selected on the basis that they demonstrated relatively constant speed and heading, and a minimal use of rudder during the data collection. The eight data runs selected for processing were taken over a span of several days, and included the influence of variable sea conditions, wind excitations, ship speeds, and ship headings. The RMS of the roll data collected ranged between 1.12 and 2.83 degrees on the eight sets. The data recorded by the DTNSRDC engineers noted each of these parameters in addition to the ship's roll motion.

As discussed previously, the use of a Rudder Roll Stabilization (RRS) device during some of the data collection will directly affect the results from the RANDEC algorithm. The RRS mechanism serves to increase the level of damping of the vessel beyond its open loop design point, accordingly the output from these runs could be expected to produce results higher in value. [Ref. 3]

B. SHIP DATA RUNS

Once the validity of the RANDEC program was confirmed, the process of analyzing ship data was begun. First, however, several points that were realized during the validation process should be reiterated. First, because the ship-time history data was the same size as Runs 1 and 2 of the validation process, the results may be expected to be of the same accuracy as achieved for the validation sets. Second, the results of y_s in the range of 90-110 percent for the RMS value are anticipated to produce the most precision of each run. And finally, as the RRS system will directly affect the RANDEC output, the data sets are discussed separately for RRS on and RRS off.

The group made up of those runs without roll stabilization were processed with selected results shown in Table II. With regard to the data, the values of ζ_{est} and T_n vary significantly from one data run to another without an ascertainable pattern. Furthermore, the trials that produced the values that most closely approximated ζ_{est}=0.08 did not occur singularly in the 90 to 110 percent RMS range contrary to the results of the validation process.

With these points in mind, consider Runs 155 and 156. The data was collected sequentially with a lapse of less than a minute between the runs. During the 40 minutes of data gathering, the ship maintained its heading and other conditions remained relatively constant. Between the two runs there is a continuity in the results obtained, both in terms of damping and roll period. This is also true for other sequential pairs of data (162, 163; 141, 142) but with differing values for modal damping and period.

Attempting to confirm the results of the individual data runs, numbers 155 and 156, as well as 162 and 163, were combined to produce a single, double-length data set. The results from the combined time histories confirm the earlier output for each of the individual runs though slightly modified. The results for the combined sets, as well as the other ship runs are contained in Appendix D.

From the data it is apparent that different environmental and operational conditions have a dramatic impact on the results obtained from the RANDEC algorithm. The results of hydrodynamic forces impinging on the ship-system produce nonlinear viscous damping effects that are not accounted for in the RANDEC code. This limitation on the design of the code rises directly from the lack of information on the ship dynamics over a wide range of environmental and operational conditions.

With time and effort these nonlinearities for the Spruance class destroyer might be analyzed and better understood using the RANDEC algorithm. To achieve this level of proficiency, however, requires the establishment of a vastly more extensive data base.

TABLE III. SELECTED SHIP DATA RESULTS.

{%RMS}	y_s	y_B	Period, secs	ω_{est} (sec^{-1})	ζ_{est}	#LAG SETS
			RUN 155			
70	1.872	1.246	13.67	0.460	0.0648	132
80	2.140	1.430	13.30	0.472	0.0641	124
90	2.407	1.542	13.30	0.472	0.0709	112
100	2.675	1.682	13.67	0.460	0.0738	98
110	2.942	1.912	13.67	0.460	0.0686	86
120	3.210	2.175	13.67	0.460	0.0619	74
			RUN 156			
70	1.748	1.218	13.67	0.460	0.0575	140
80	1.998	1.238	13.67	0.460	0.0762	134
90	2.248	1.230	13.33	0.471	0.0960	122
100	2.498	1.471	13.67	0.460	0.0842	100
110	2.747	1.634	14.00	0.449	0.0827	88
120	2.997	1.820	14.00	0.449	0.0794	80
			RUN 162			
70	2.699	2.415	14.33	0.439	0.0177	118
80	3.085	2.738	14.33	0.439	0.0190	114
90	3.470	3.042	14.67	0.428	0.0210	104
100	3.856	3.419	14.67	0.428	0.0191	98
110	4.242	3.731	14.67	0.428	0.0204	88
120	4.627	4.026	14.30	0.439	0.0222	84

V. CONCLUSIONS

The study has shown that the RANDEC procedure may indeed have practical applications with regard to estimating the dynamics of naval vessels. The validation process, based upon approximated ship values, yielded the expected dynamic characteristics of the idealized system model. The RANDEC algorithm was validated for a white-noise type of input.

Application of the developed RANDEC program to the available ship data base result in a wide dispersion of damping level estimates for the ship. The differences in damping levels arise from the influence of the hydrodynamic wave effects upon the ship system. Of particular note are the nonlinearities introduced as a result of the damping, which is roll amplitude dependent.

Future work on this subject should include the use of standard ocean modelling techniques to generate the forcing function for input into the ship validation model. Results obtained would serve to guide changes to increase the robustness of the RANDEC algorithm and confirm the validity of the procedure under a wider range of modelled sea states. Additionally, the ship model used during the validation process should allow for damping increases to clarify whether the RANDEC signature would be applicable to a physical (ship) system whose dynamics were improved by the use of state variable feedback.

APPENDIX A: RANDOM DECREMENT PROGRAM

```
10 ' Filename is .. A:RANDECFINAL.BAS ; 08 AUGUST '91
   ' Purpose is apply Random Decrement process
   ' to a time history record obtained from a
   ' data file stored on a floppy disk.
   '  Modified to establish max. no. for threshold crossings
   ' $DYNAMIC
   'xCOMMON XS():  ' Saving grace statement
   XMAX = 10000:  ' 2000 is normal upper  limit
   NSAMP = 200:  ' NSAMP is no. of samples in each lagged set
   NLAG = 150: ' NLAG is max. expected value of Lagged sets
100 DIM X1(XMAX), XS(NSAMP), XAVE(NSAMP)

   ' Identify source of ASCII data file, NEXT LINE ALTERED TO READ FROM FLOPPY.
   A$ = "c:\thesis\zeta2\Re10k_2.ASC":  ' Set up file name of data source
   OPEN "I", #1, A$
   ' IDENTIFY OUTPUT FILE FOR DATA.
   OPEN "c:\thesis\zeta2\10k_270.ASC" FOR OUTPUT AS #2
   'INPUT YS VALUE
   YS = 1.80857 * (.7)
200 ' Read data file
   'INPUT #1, R, X1(1), X2: RMS1 = X1(1): LPRINT TAB(5); "RMS1 ="; RMS1
   FOR I = 1 TO XMAX: ' Upper limit is estbld. above
   'INPUT #1, R, X1(I), X2
   INPUT #1, X1(I)
   X1(I) = X1(I)
   'PRINT USING "#.####"; i; X1(i)
   ' IF (I > 3990) THEN PRINT I; R; X1(I); X2
   NEXT I
   CLOSE #1
   'GOTO 1000
300 ' Screen the data file for threshold crossings
   ' and establish lagged samples
   'INPUT "ENTER YS:"; YS: ' Option for keyboard entries

    'YS = 4.032:        ' Establish threshold crossing value
    ' Find Max. no. of threshold crossings for data set
    count = 0:  ' Initialize count index for S/R at "2500"
    FOR k = 200 TO (XMAX - 250)
    IF (X1(k - 1) - YS) < 0! AND (X1(k) - YS) > 0! THEN GOSUB 2500
    IF (X1(k - 1) - YS) > 0! AND (X1(k) - YS) < 0! THEN GOSUB 2500
   NEXT k
   ' Output from above do-loop is the count index value
    'LPRINT USING "####"; k
```

```
    NLAG = count:  ' NL set to max. no. of threshold crossings
    ' NLAG = 15 :  ' NL = Number of time lagged sets, arbitrary no.
    GOSUB 2600:   ' Printout of ability to find max. of NLAG
    'fOR N = LOW TO (INDEX + 200)
    'CHECK = CHECK + (X1(N))
    'NEXT N
    'CORRECT = CHECK / (INDEX + 200 - LOW)
    'LPRINT USING "###.###"; CHECK; CORRECT
320   ' Find NLAG Data sets & apply time shift approx.
   ' When search is done, program has XAVE(NSAMP)
    I = 1:        ' Set index on set number count
    FOR k = 200 TO (XMAX - 250)
    IF (X1(k - 1) - YS) < 0! AND (X1(k) - YS) > 0! THEN GOSUB 2000
    IF (X1(k - 1) - YS) > 0! AND (X1(k) - YS) < 0! THEN GOSUB 2000
    IF I > NLAG THEN GOTO 360:  ' Escape from K doloop using "I"
    NEXT k
360  ' Normalize the sum by "NLAG" to obtain averages
    FOR J = 1 TO NSAMP
    'UNNECESSARY FOR FURTHER BIASING ON DATA AS A RESULT OF GRAPHIC OUTPUT
    XAVE(J) = (XAVE(J) / NLAG): ' - CORRECT
    NEXT J

400 ' Print results to check process logic
    ' FOR J = 1 TO 20
    ' LPRINT USING "####.##"; T(1, J); Y(1, J); T(2, J); Y(2, J); T(3, J); Y(3, J); T(4, J); Y(4, J)
    ' NEXT J
    ' Print shift fractions
    'LPRINT TAB(10); "Shift Fractions, FSHFT(I), are:"
    'LPRINT USING "####.###"; FSHFT(1); FSHFT(2); FSHFT(3); FSHFT(4); FSHFT(5)
    ' LPRINT TAB(20); "No. of Sets Averaged ="; NL
    'LPRINT TAB(10); "** Shifted Data Sets **"; TAB(43); "(XS)ave"; TAB(53); "Time"
  FOR J = 1 TO NSAMP
    'LPRINT USING "####.###"; XS(1, J); XS(2, J); XS(3, J); XS(4, J); XS(5, J); XAVE(J); (J - 1) / 3
    ' PRINT USING "####.###"; (J - 1) / 3; XAVE(J): ' Print out for ASCII file data logging
     PRINT #2, USING "####.###"; XAVE(J): 'modified from above line to allow for cricket graph
  NEXT J
     CLOSE #2
1000 END

2000 ' S/R to Obtain Lagged Sample for the Shifted Data Set XS(I,J)
    FOR J = 1 TO NSAMP
    IF J = 1 THEN GOSUB 2100:  ' Determine shift fraction
    '  Perform linear interpolation to find shifted data sets
    XS(J) = X1(k + J - 2) + FSHFT * (X1(k + J - 1) - X1(k + J - 2))
    NEXT J
    GOSUB 2200:  ' Implement addition of set terms
    I = I + 1: ' Increase number index on lagged set
    RETURN

2100 ' S/R to find Shift Fraction for the "I-th" Lagged set
```

```
FSHFT = (YS - X1(k - 1)) / (X1(k) - X1(k - 1))
RETURN

2200  ' Process Shifted Data Set XS(NSAMP) to find XAVE(NSAMP)
   FOR J = 1 TO NSAMP
   XAVE(J) = XAVE(J) + XS(J)
   NEXT J
   ' PRINT I; XS(1); XS(NSAMP): ' for debugging purposes
   RETURN

2500 ' S/R to establish lag count in data set
  ' .. Count increased by one each time the data set
  '    crosses the threshold value YS and triggers this S/R
  count = count + 1
  'IF COUNT = 1 THEN LOW = K
  'INDEX = K
  PRINT USING "######"; count; k
  RETURN

2600  ' Print out max. value of NL in data set
  'PRINT TAB(5); "YS ="; YS; TAB(40); "Max. NLAG ="; NLAG
  PRINT USING "####.######"; YS; NLAG
  RETURN
```

APPENDIX B: RANDOM RESPONSE PROGRAM

```
10 ' File = A:RANRESP1.BAS     Date: 11 June 1991
   ' Generate Random function using Monte Carlo approach
   ' Apply random fn. to 2nd. order linear system using
   ' digital processing.
   ' $DYNAMIC
   'xcommon X1!(),X2!(),R!()
100 ' Set up dimension statements, etc.
   DIM R(10010), X1(10010), X2(10010), PHI(2, 2), GAMMA(2)
   RANDOMIZE TIMER
   OPEN "A:\R1OK.ASC" FOR OUTPUT AS #2
110 ' Establish 2nd Order Plant for Ts = 0.3333 sec.
   ' Wn = 0.40 /sec., Zeta = 0.08
   DATA 0.99119 , 0.32879, -0.05261, 0.97015
   DATA 0.05507, 0.32879
  FOR I = 1 TO 2: FOR J = 1 TO 2: READ PHI(I, J): NEXT J
  NEXT I
  FOR I = 1 TO 2: READ GAMMA(I): NEXT I
  ' Echoe Check on data read statements
  ' PRINT USING "###.#####"; PHI(1, 1); PHI(1, 2)
  ' PRINT USING "###.#####"; PHI(2, 1); PHI(2, 2)
  ' PRINT USING "###.#####"; GAMMA(1); GAMMA(2)
200 ' Establish Random Function
  XMAX = 10000: FOR J = 1 TO XMAX
  R(J) = 0!
  FOR I = 1 TO 12
  XVAL = RND - .5: R(J) = R(J) + XVAL
  NEXT I
  ' PRINT USING "###.####"; J; R(J)
  NEXT J
210 ' Option to find mean and RMS
  GOSUB 2000
220 ' Remove Mean from random signal
   FOR I = 1 TO XMAX
   R(I) = R(I) - MEAN: NEXT I

300 ' Find 2nd Order System Response to Random Forcing Function
   ' That has a zero mean due to step just above..
   X1(1) = 0!: X2(1) = 0!
```

```
'PRINT USING "###.####"; R(1); X1(1); X2(1); RMS
FOR I = 1 TO (XMAX - 1)
X1(I + 1) = PHI(1, 1) * X1(I) + PHI(1, 2) * X2(I) + GAMMA(1) * R(I)
X2(I + 1) = PHI(2, 1) * X1(I) + PHI(2, 2) * X2(I) + GAMMA(2) * R(I)
'PRINT USING "###.####"; R(I + 1); X1(I + 1); X2(I + 1); RMS
NEXT I

400 ' Find RMS values for Output response, RMS1 & RMS2
GOSUB 2100
' PRINT TAB(5); "XMAX ="; XMAX
' PRINT TAB(3); "Input R(I), RMS  ="; RMS
' PRINT "Output X1(I), RMS1 ="; RMS1
' PRINT "Output X2(I), RMS2 ="; RMS2

450 ' Remove Mean from output signals
FOR I = 1 TO XMAX
X1(I) = X1(I) - MEAN1
X2(I) = X2(I) - MEAN2
NEXT I

500 ' Print the results.
' Note first output ROW contains the RMS values.
PRINT USING "####.####"; RMS; RMS1; RMS2
' Remaining row outputs are data..
FOR I = 1 TO XMAX
PRINT #2, USING "####.####"; X1(I): 'I + 1; X1(I); X2(I)
NEXT I

1000 END

2000 ' ** S/R to Find mean and RMS
MEAN = 0!: FOR J = 1 TO XMAX
MEAN = MEAN + R(J)
NEXT J
MEAN = MEAN / XMAX
' PRINT TAB(5); "Mean ="; MEAN
' Find RMS
RMS = 0!: FOR J = 1 TO XMAX
RMS = RMS + ((R(J) - MEAN) ^ 2)
NEXT J
RMS = SQR(RMS / (XMAX - 1))
' PRINT TAB(6); "RMS ="; RMS
RETURN
```

```
2100 ' S/R to find RMS1 & RMS2 from X1(I) & X2(I)
   MEAN1 = 0!: MEAN2 = 0!: FOR J = 1 TO XMAX
   MEAN1 = MEAN1 + X1(J): MEAN2 = MEAN2 + X2(J)
   NEXT J
   MEAN1 = MEAN1 / XMAX: MEAN2 = MEAN2 / XMAX

   RMS1 = 0!: RMS2 = 0!: FOR J = 1 TO XMAX
   RMS1 = RMS1 + ((X1(J) - MEAN1) ^ 2)
   RMS2 = RMS2 + ((X2(J) - MEAN2) ^ 2)
   NEXT J
   RMS1 = SQR(RMS1 / (XMAX - 1))
   RMS2 = SQR(RMS2 / (XMAX - 1))
   RETURN
```

APPENDIX C: VALIDATION RESULTS

A. Run 1 with 4000 points

TABLE IV. RANDEC OUTPUT FOR RUN 1.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, (sec^{-1})	ζ_{est}	#LAG SETS
RUN 1						
70	2.688	1.558	16.33	0.385	0.0868	112
80	3.072	1.743	16.67	0.377	0.0902	110
90	3.456	2.053	17.0	0.370	0.0829	102
100	3.840	2.131	16.33	0.385	0.0937	92
110	4.224	2.581	16.33	0.385	0.0784	74
120	4.608	2.876	16.33	0.385	0.0750	70

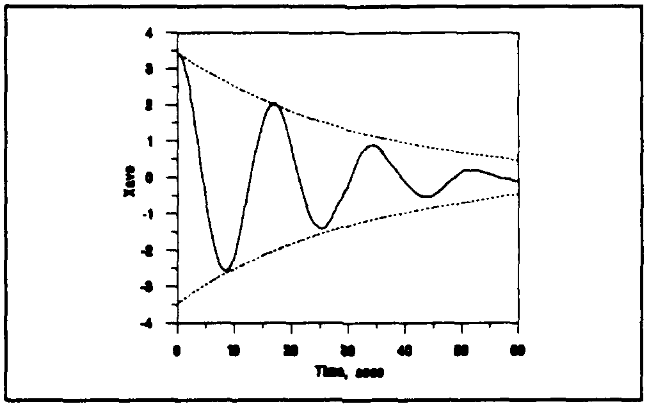

Figure 6. Run 1 with y_s set to 90 percent RMS.

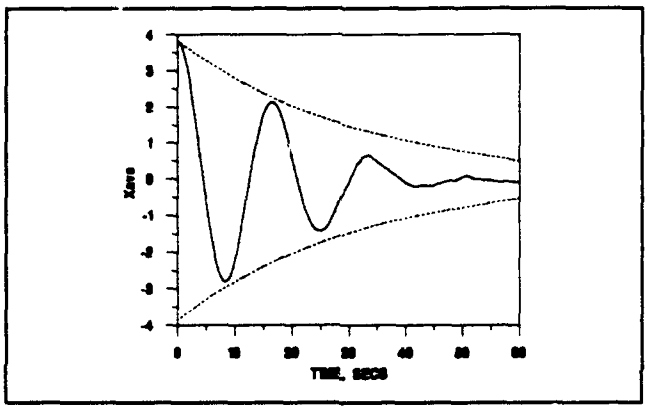

Figure 7. Run 1 with y_s set equal to RMS.

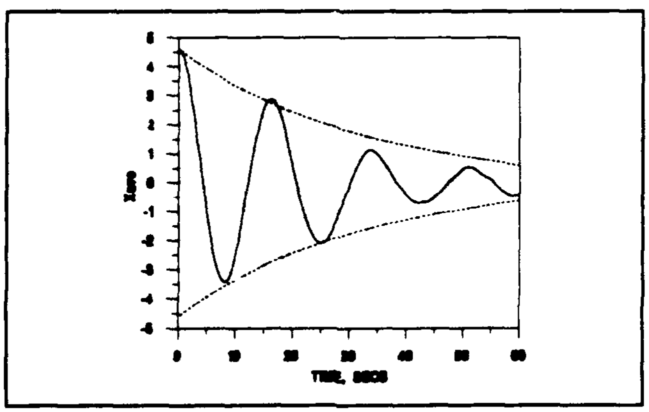

Figure 8. RANDEC with y_s set to 1.2 RMS.

B. Run 2 with 4000 points

TABLE V. RANDEC OUTPUT FOR RUN 2 WITH 4000 POINTS.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est} ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 2						
70	2.665	1.720	15.67	0.401	0.0697	112
80	30.45	1.984	15.67	0.401	0.0682	110
90	3.426	2.078	15.67	0.401	0.0796	102
100	3.807	2.224	15.67	0.401	0.0856	96
110	4.187	2.226	15.67	0.401	0.1006	88
120	4.568	2.351	15.33	0.410	0.1057	80

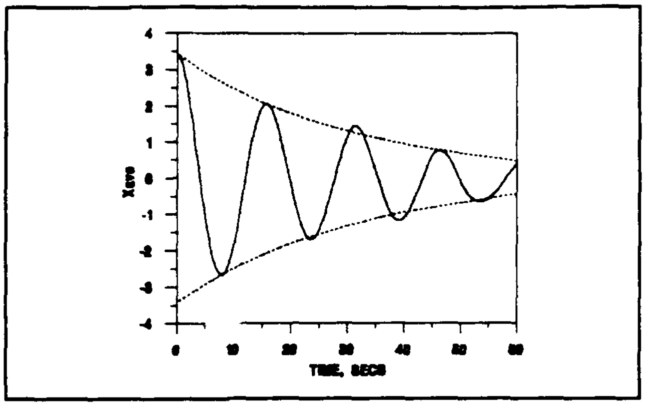

Figure 9. Run 2 with y_s set to 90 percent of RMS.

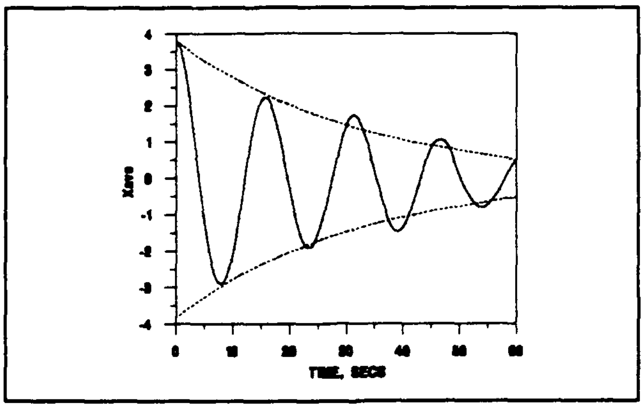

Figure 10. Run 2 with y_s set to the data RMS value.

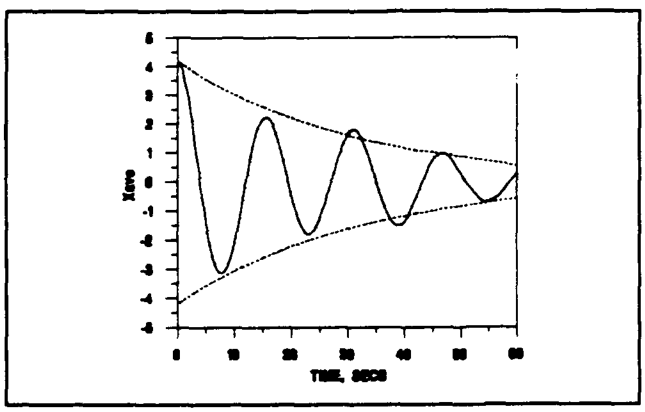

Figure 11. Run 2 with y_s set to 110 percent RMS.

C. **Run 3 with 6000 points.**

TABLE VI. RUN 3 RANDEC OUTPUT FOR 6000 POINTS.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, $(secs^{-1})$	ζ_{est}	#LAG SETS
Run 3						
70	2.792	2.014	15.66	0.401	0.0520	179
80	3.191	2.429	15.66	0.401	0.0434	161
90	3.590	2.532	15.66	0.401	0.0556	143
100	3.989	2.643	15.33	0.410	0.0605	127
110	4.388	2.890	15.33	0.410	0.0665	123
120	4.787	2.976	15.67	0.401	0.0757	102

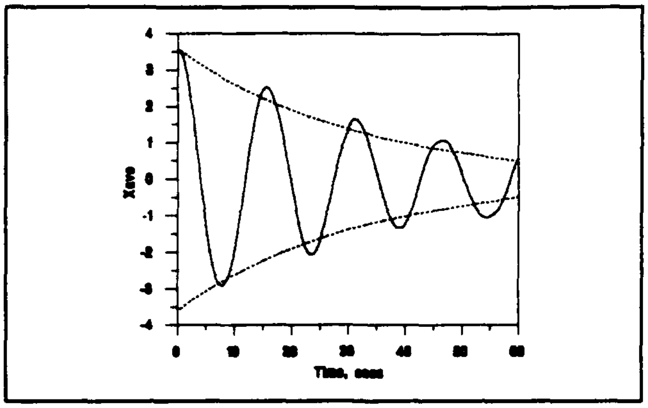

Figure 12. Run 3 with y_s set to 90 percent RMS.

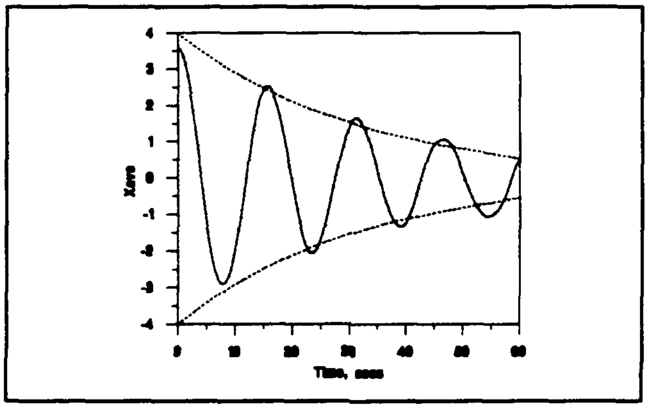

Figure 13. Run 3 with y_s set to the RMS value.

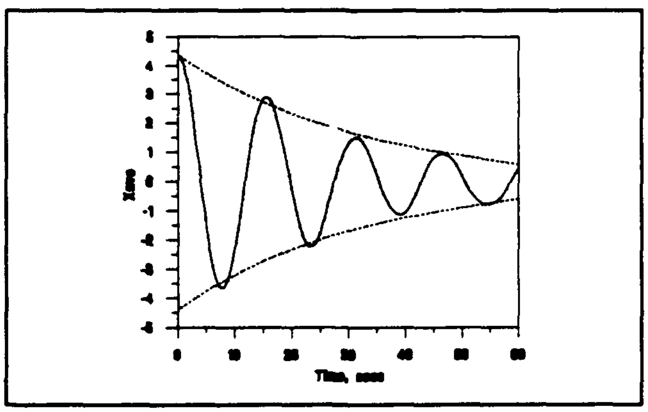

Figure 14. Run 3 with y_s set to 110 percent of RMS.

D. **Run 4 with 8000 points.**

TABLE VII. RANDEC RESULTS FOR 8000 POINT DATA SET.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 4						
70	2.822	1.875	16.33	0.385	0.0651	260
80	3.226	1.976	16.33	0.385	0.0780	236
90	3.629	2.274	16.00	0.393	0.0744	224
100	4.032	2.500	16.00	0.393	0.0761	194
110	4.435	2.844	15.67	0.401	0.0707	180
120	4.838	3.062	15.67	0.401	0.0728	162

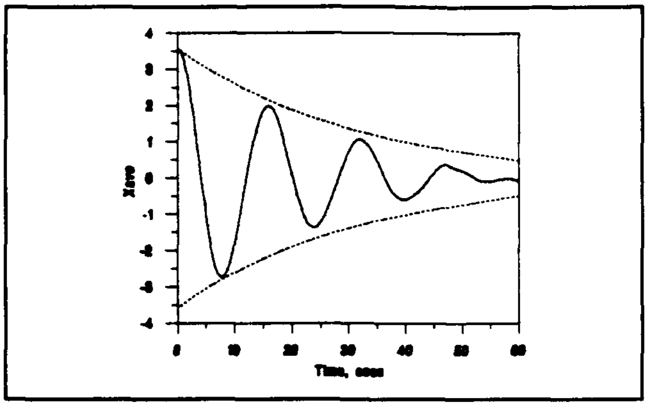

Figure 15. Run 4 with y_s set to 90 percent RMS.

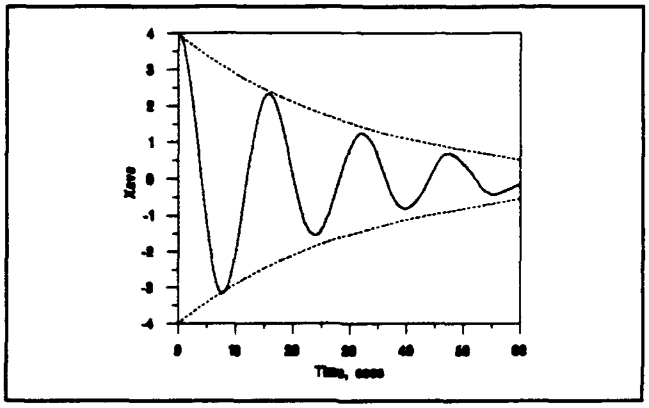

Figure 16. Run 4 with y_s set to RMS.

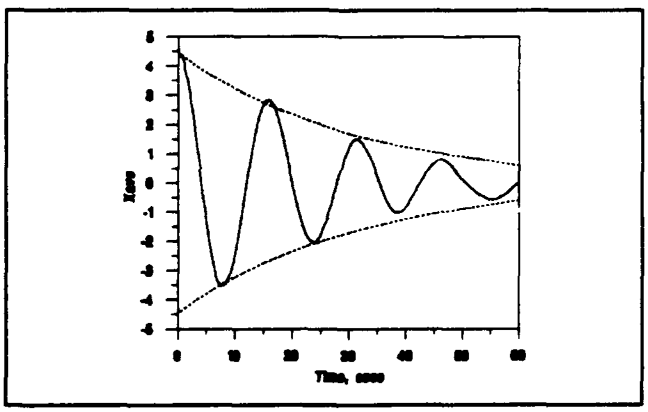

Figure 17. Run 4 with y_s set to 110 percent RMS.

E. **Run 5 with 10000 points.**

TABLE VIII. RUN 4 WITH 10000 POINTS RANDEC RESULTS.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 5						
70	2.785	1.588	16.00	0.393	0.0894	310
80	3.182	1.775	16.00	0.393	0.0929	290
90	3.580	2.000	16.00	0.393	0.0927	268
100	3.978	2.332	15.67	0.401	0.0850	242
110	4.376	2.650	16.00	0.393	0.0798	220
120	4.774	2.968	16.00	0.393	0.0756	204

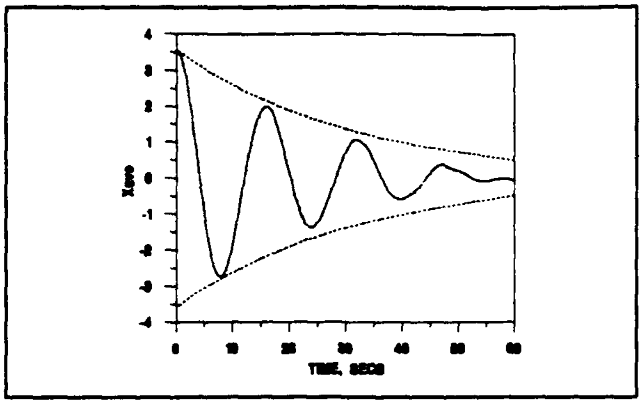

Figure 18. Run 5 with y_s set to 90 percent of RMS.

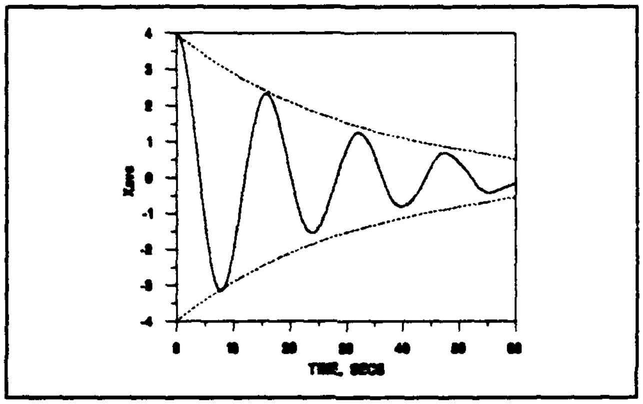

Figure 19. Run 5 with y_s set to the RMS for the data.

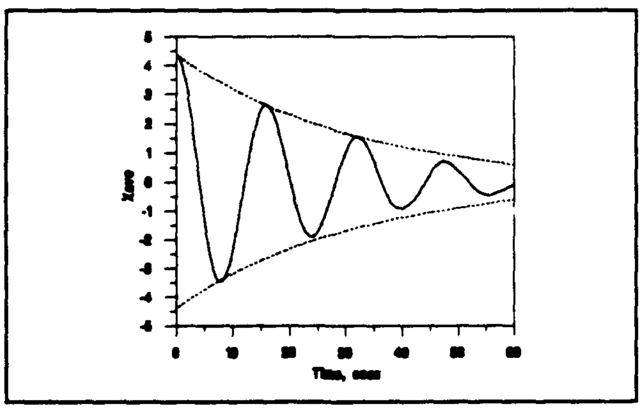

Figure 20. Run 5 with y_s set to 110 percent RMS.

F. **Run 6 with 15000 points.**

TABLE IX. RANDEC RESULTS FOR RUN 5 WITH 15000 POINTS.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 6						
70	2.628	1.715	15.33	0.410	0.0679	505
80	3.003	1.837	15.33	0.410	0.0782	461
90	3.379	2.104	15.33	0.410	0.0754	431
100	3.754	2.277	15.33	0.410	0.0796	391
110	4.129	2.500	15.33	0.410	0.0799	339
120	4.505	2.743	15.33	0.410	0.0790	321

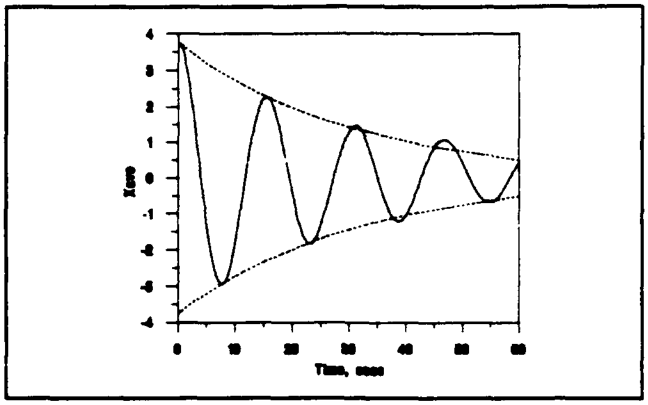

Figure 21. Run 6 with y_s set equal to RMS.

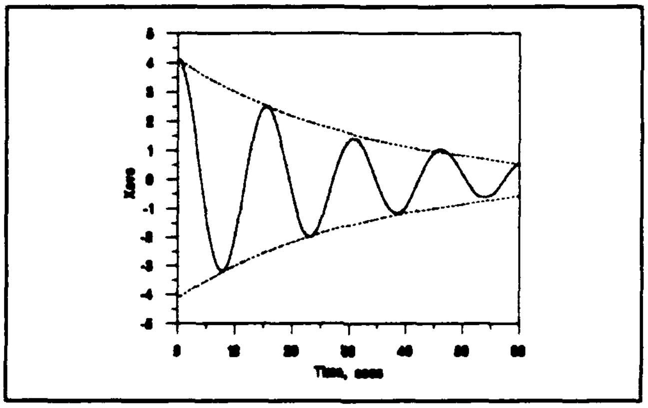

Figure 22. Run 6 with y_s equal to 110 percent of RMS.

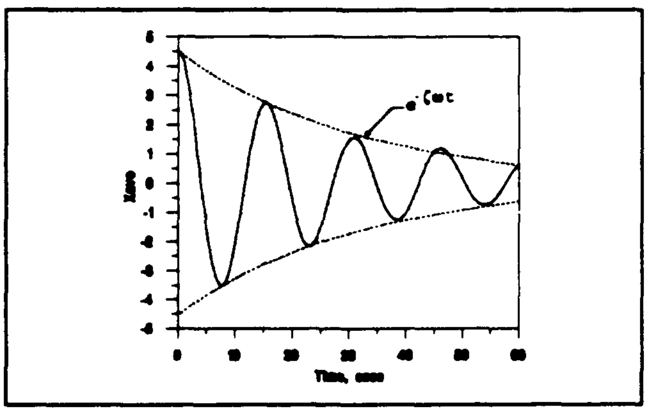

Figure 23. Run 6 with y_s equal to 120 percent RMS.

APPENDIX D: SHIP RESULTS

A. Run 108

TABLE X. RESULTS OF THE RANDEC ALGORITHM FOR RUN 108.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 108						
70	0.781	0.424	14.67	0.428	0.0972	157
80	0.892	0.427	15.00	0.419	0.1173	153
90	1.004	0.484	14.67	0.428	0.1161	126
100	1.115	0.522	14.33	0.439	0.1208	120
110	1.227	0.572	14.67	0.428	0.1214	106
120	1.338	0.576	14.67	0.428	0.1342	84

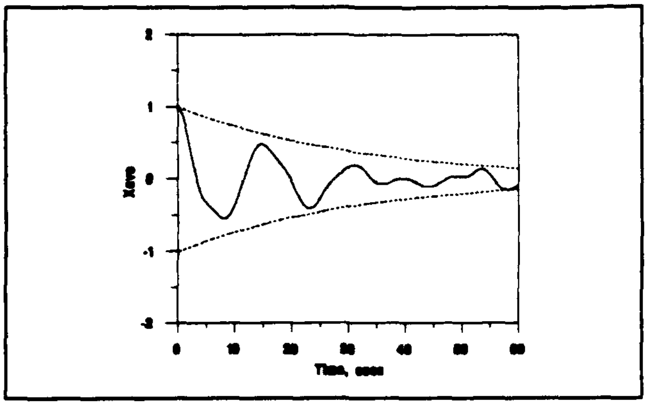

Figure 24. Run 108 with y_s set to 90 percent RMS.

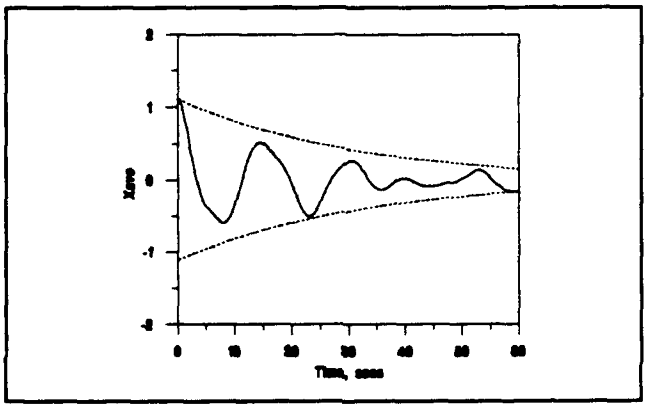

Figure 25. Run 108 with y_s set to data RMS.

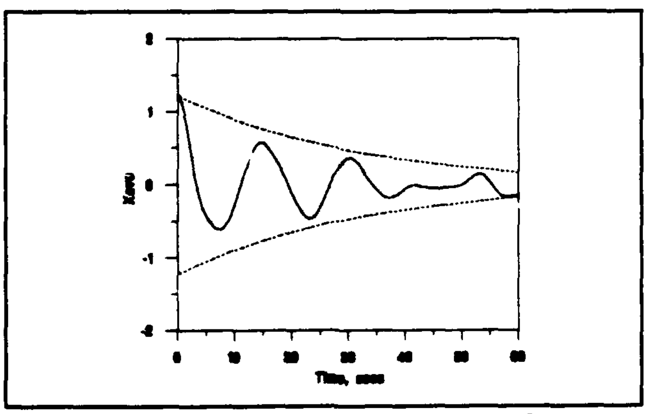

Figure 26. Run 108 with y_s set to 110 percent data RMS.

B. Run 114

TABLE XI. RESULTS OF THE RANDEC CODE FOR RUN 114.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 114						
70	1.352	0.731	13.67	0.460	0.0978	140
80	1.545	0.818	13.33	0.471	0.1012	128
90	1.738	0.901	13.00	0.483	0.1045	116
100	1.931	0.984	13.30	0.472	0.1073	104
110	2.124	1.292	13.30	0.472	0.0791	94
120	2.317	1.421	13.67	0.460	0.0778	78

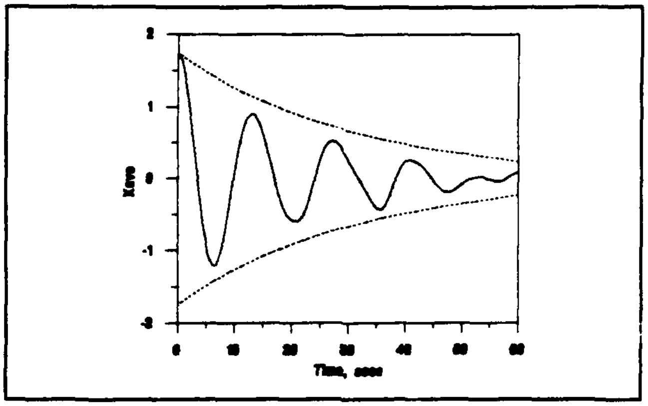

Figure 27. Run 114 with y_s set to 90 percent of RMS.

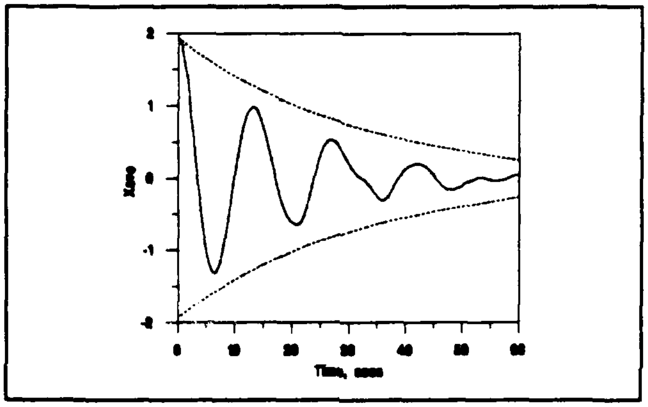

Figure 28. Run 114 with y_s at RMS.

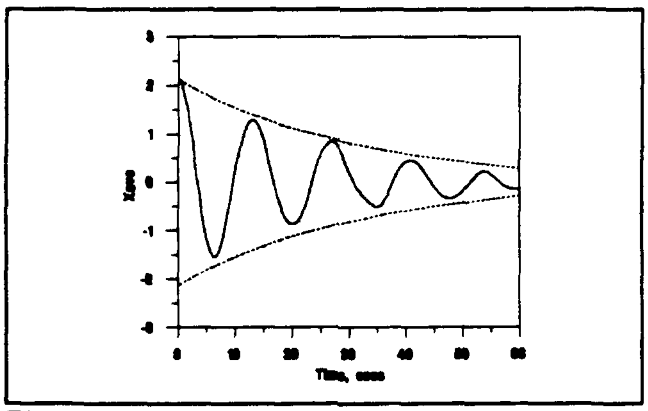

Figure 29. Run 114 with y_s set to 1.1 RMS.

C. Run 141

TABLE XII. RANDEC RESULTS FOR RUN 141.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, (secs^{-1})	ζ_{est}	#LAG SETS
RUN 141						
70	1.681	1.470	14.30	0.439	0.0213	124
80	1.921	1.661	14.67	0.428	0.0231	120
90	2.161	1.845	14.30	0.439	0.0252	112
100	2.401	2.062	14.30	0.439	0.0242	106
110	2.641	2.272	14.30	0.439	0.0240	92
120	2.881	2.578	14.30	0.439	0.0177	80

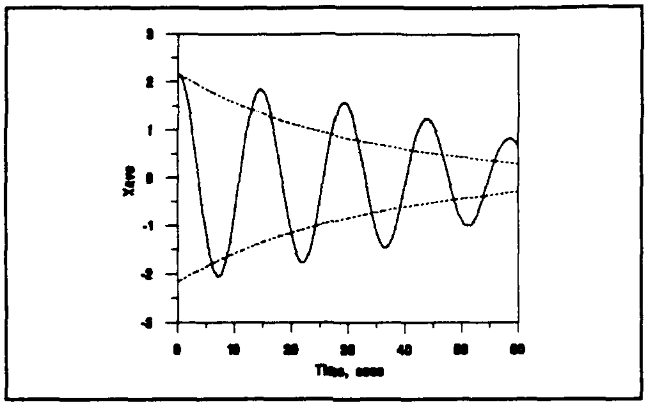

Figure 30. Run 141 with y_s set to 90 percent RMS.

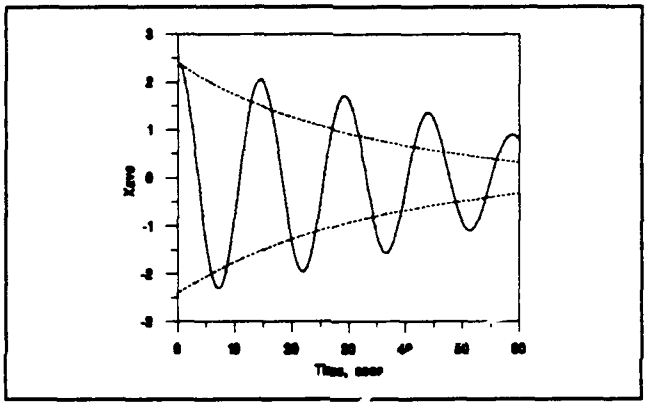

Figure 31. Run 141 with y_s set to the data RMS.

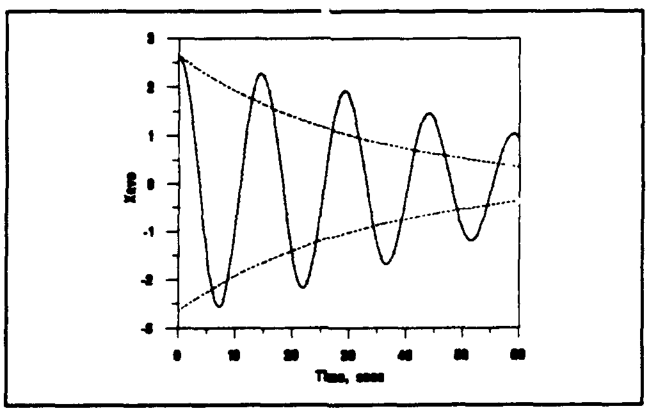

Figure 32. Run 141 with y_s set to 110 percent RMS.

D. Run 142

TABLE XIII. RANDEC RESULTS FOR RUN 142.

(%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, (secs^{-1})	ζ_{est}	#LAG SETS
RUN 142						
70	1.983	1.799	14.00	0.449	0.0155	130
80	2.266	1.985	14.00	0.449	0.0211	120
90	2.549	2.247	14.00	0.449	0.0201	108
100	2.832	2.488	14.00	0.449	0.0206	92
110	3.116	2.750	14.00	0.449	0.0199	86
120	3.399	3.010	14.00	0.449	0.0193	82

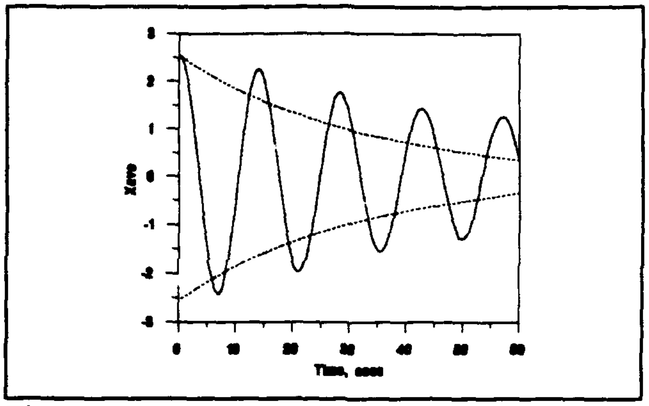

Figure 33. Run 142 with y_s set to 90 percent RMS.

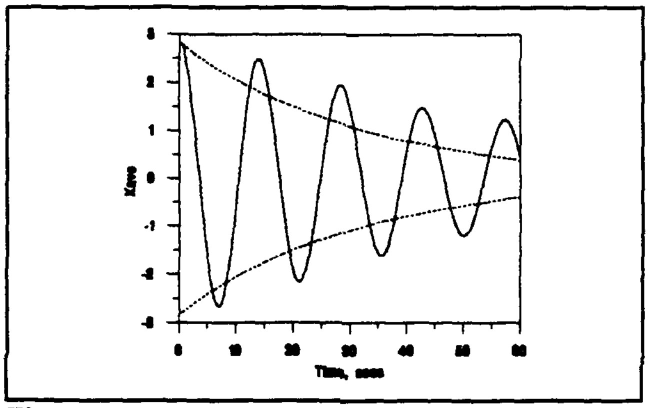

Figure 34. Run 142 with y_s set to data RMS.

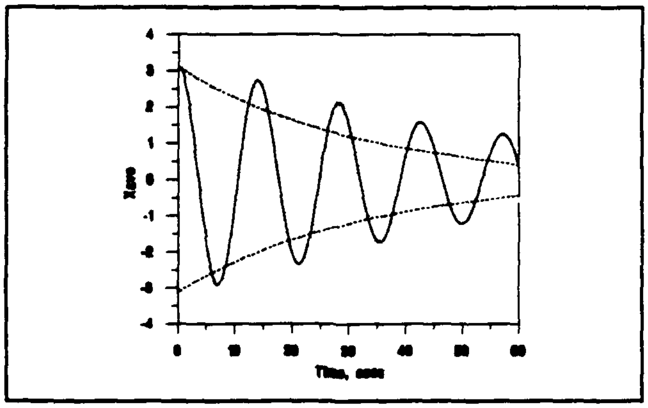

Figure 35. Run 142 with y_s set to 110 percent of RMS.

E. Run 155

TABLE XIV. RUN 155 RESULTS FROM THE RANDEC ALGORITHM.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, (secs^{-1})	ζ_{est}	#LAG SETS
RUN 155						
70	1.872	1.246	13.67	0.460	0.0648	132
80	2.140	1.430	13.30	0.472	0.0641	124
90	2.407	1.542	13.30	0.472	0.0709	112
100	2.675	1.682	13.67	0.460	0.0738	98
110	2.942	1.912	13.67	0.460	0.0686	86
120	3.210	2.175	13.67	0.460	0.0619	74

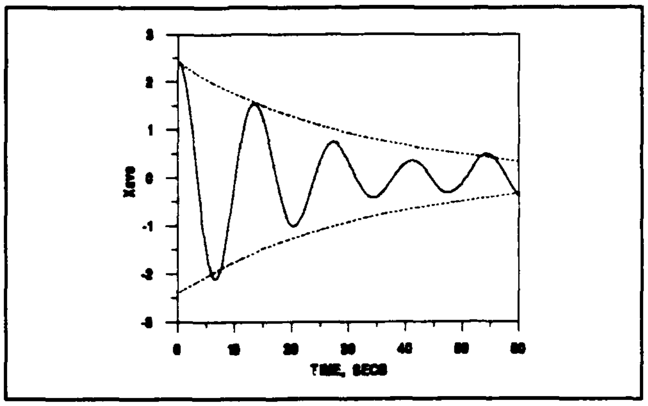

Figure 36. Run 155 with y_s set to 90 percent RMS.

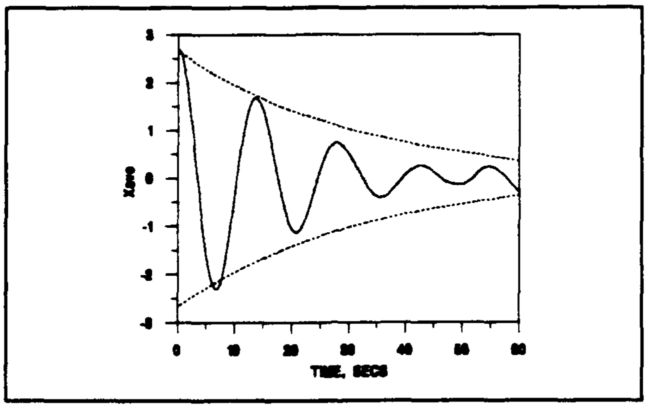

Figure 37. Run 155 with y_s at RMS.

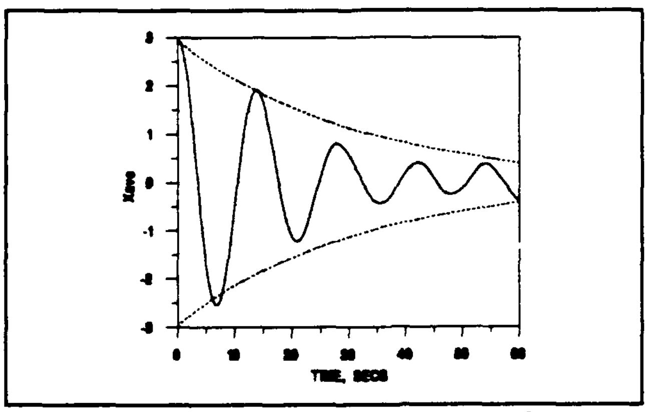

Figure 38. Run 155 with y_s set to 110 percent RMS.

F. Run 156

TABLE XV. RUN 156 RESULTS FOR THE RANDEC ALGORITHM.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 156						
70	1.748	1.218	13.67	0.460	0.0575	140
80	1.998	1.238	13.67	0.460	0.0762	134
90	2.248	1.230	13.33	0.471	0.0960	122
100	2.498	1.471	13.67	0.460	0.0842	100
110	2.747	1.634	14.00	0.449	0.0827	88
120	2.997	1.820	14.00	0.449	0.0794	80

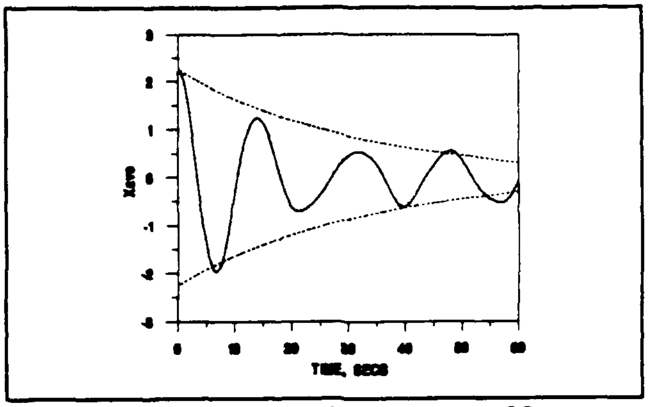

Figure 39. Run 156 with y_s set to 90 percent RMS.

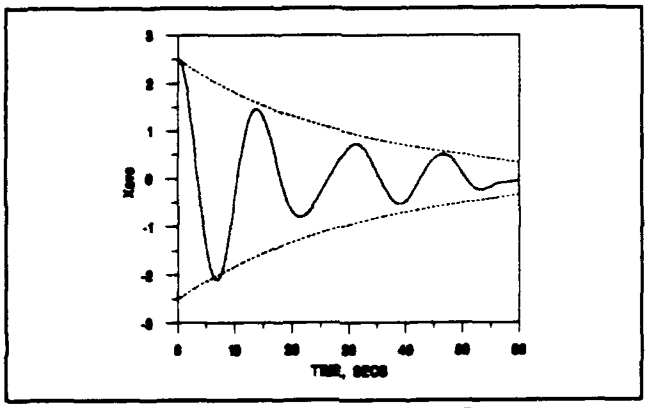

Figure 40. Run 156 with y_s at RMS.

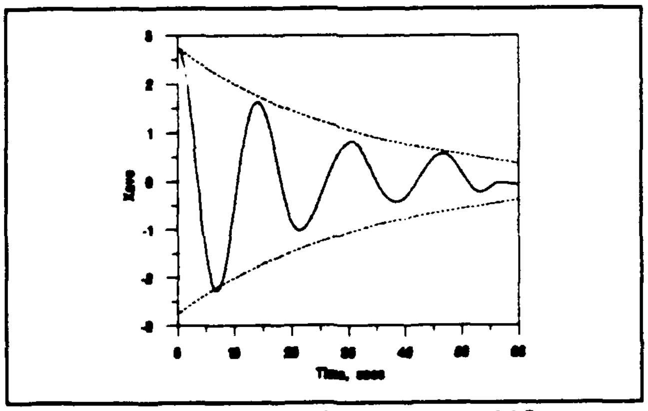

Figure 41. Run 156 with y_s set to 110 percent RMS.

G. Run 162

TABLE XVI. RUN 162 OUTPUT DATA FOR VARIOUS Y_S VALUES FROM RANDEC.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUN 162						
70	2.699	2.415	14.33	0.439	0.0177	118
80	3.085	2.738	14.33	0.439	0.0190	114
90	3.470	3.042	14.67	0.428	0.0210	104
100	3.856	3.419	14.67	0.428	0.0191	98
110	4.242	3.731	14.67	0.428	0.0204	88
120	4.627	4.026	14.30	0.439	0.0222	84

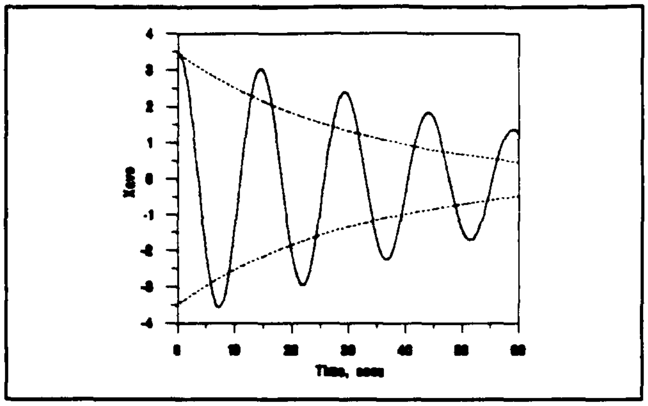

Figure 42. Run 162 with y_s equal to 90 percent of RMS.

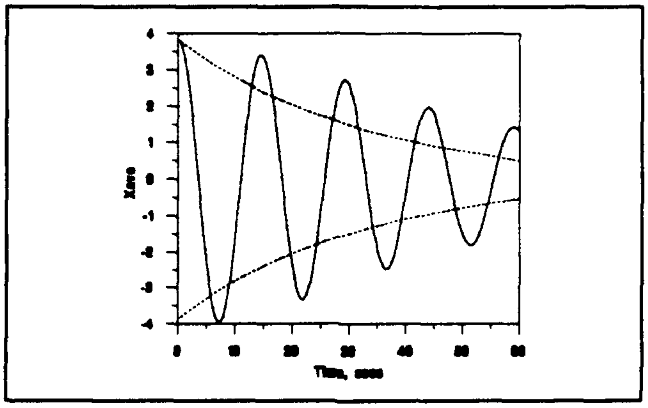

Figure 43. Run 162 with y_s set to data RMS value.

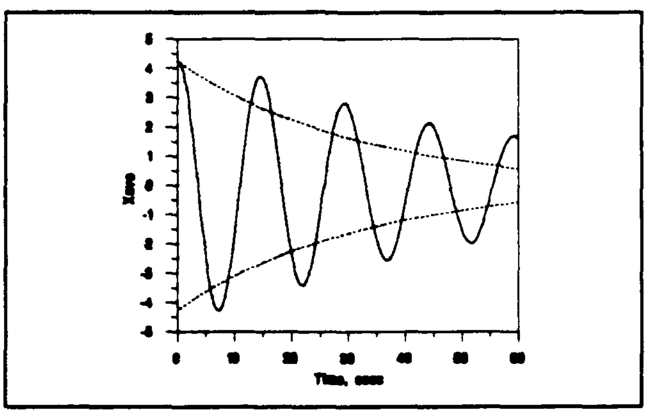

Figure 44. Run 162 with y_s at 110 percent of RMS.

H. Run 163

TABLE XVII. RANDEC RESULTS FOR RUN 163 SHIP DATA.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, (secs^{-1})	ζ_{est}	#LAG SETS
RUN 163						
70	1.991	1.579	15.00	0.419	0.0369	127
80	2.275	1.744	14.67	0.428	0.0423	113
90	2.559	1.981	15.00	0.419	0.0408	105
100	2.844	2.219	14.67	0.428	0.0395	91
110	3.128	2.532	14.67	0.428	0.0337	85
120	3.413	2.718	14.67	0.428	0.0362	83

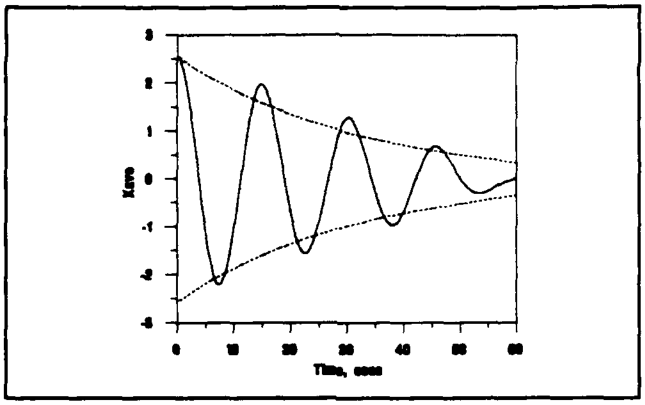

Figure 45. Run 163 with y_s set to 90 percent RMS.

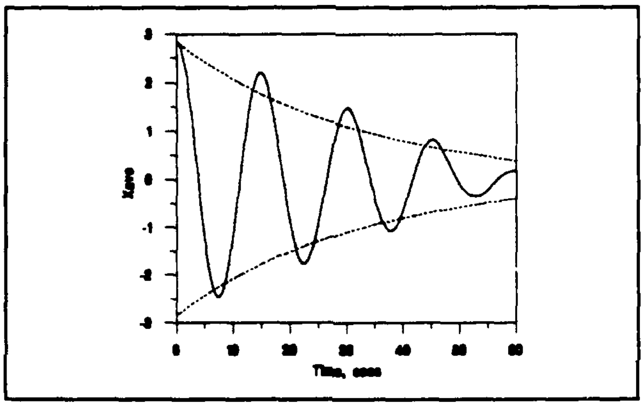

Figure 46. Run 163 with y_s set to data RMS.

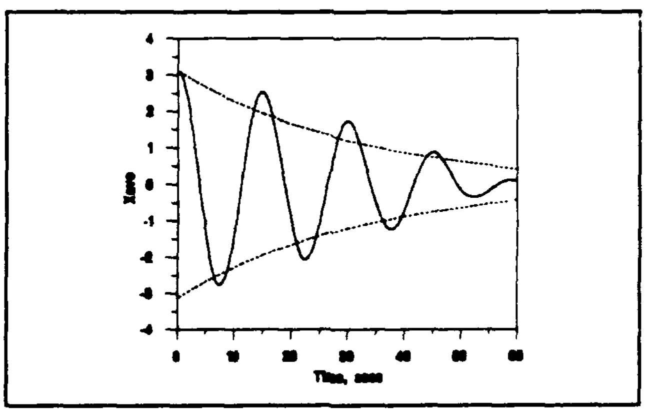

Figure 47. Run 163 with y_s set to 110 percent RMS.

I. Combination of Run 155 and Run 156

TABLE XVIII. RANDEC OUTPUT FOR RUN 155 AND RUN 156 COMBINED.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUNS 155 & 156 COMBINED						
70	1.811	1.175	13.33	0.471	0.0688	280
80	2.070	1.232	13.33	0.471	0.0825	258
90	2.328	1.442	13.33	0.471	0.0930	224
100	2.587	1.600	13.67	0.460	0.0765	206
110	2.846	1.724	13.33	0.471	0.0797	184
120	3.104	1.928	13.67	0.460	0.0758	156

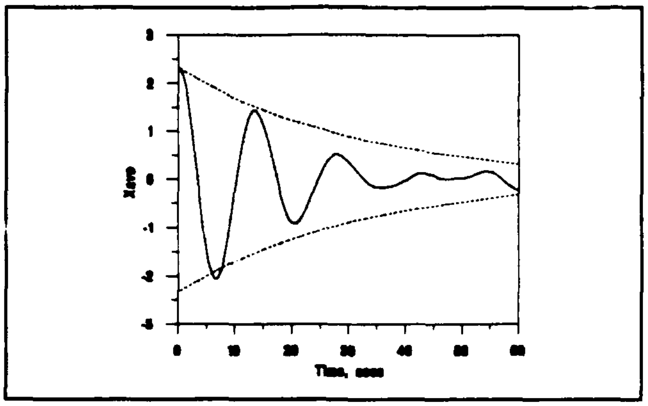

Figure 48. Run 155 and 156 combined at y_s set to 0.9 RMS.

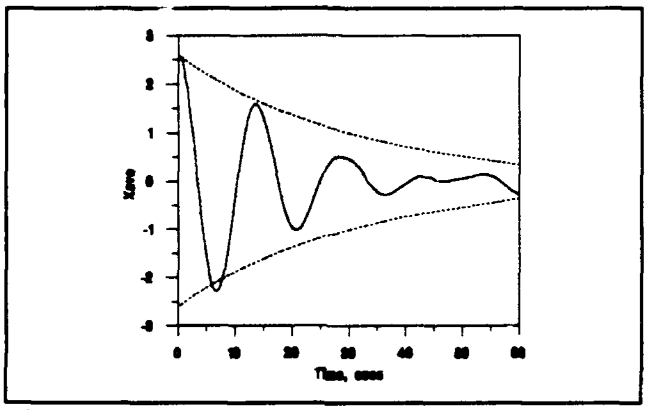

Figure 49. Run 155 and 156 combined with y_s set to RMS.

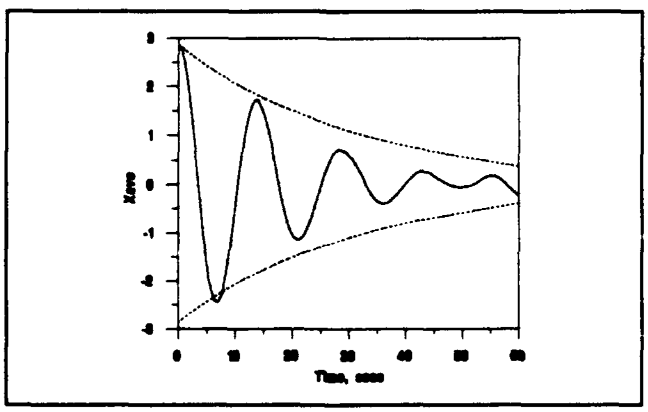

Figure 50. Run 155 and 156 with y_s set to 1.1 RMS.

J. Combination of Run 162 and Run 163

TABLE XIX. RANDEC OUTPUT FOR COMBINATION OF RUN 162 AND RUN 163.

{%RMS}	y_s	y_B	PERIOD, secs	ω_{est}, ($secs^{-1}$)	ζ_{est}	#LAG SETS
RUNS 162 & 163 COMBINED						
70	2.388	2.034	14.67	0.428	0.0255	251
80	2.729	2.251	14.67	0.428	0.0306	231
90	3.070	2.593	14.67	0.428	0.0269	211
100	3.411	2.922	14.67	0.428	0.0246	193
110	3.752	3.146	14.67	0.428	0.0280	183
120	4.093	3.374	14.67	0.428	0.0307	174

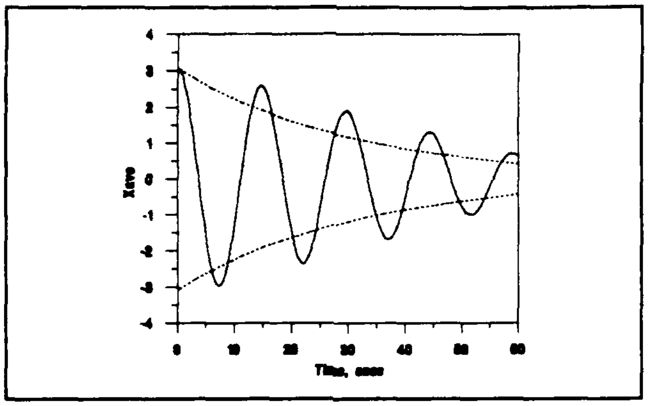

Figure 51. Combination with y_s equal to 90 percent RMS.

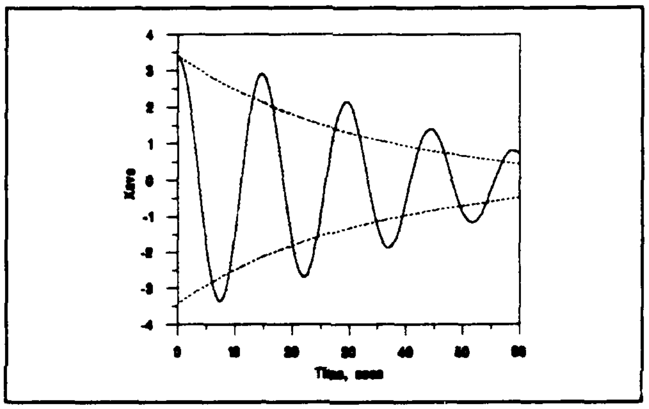

Figure 52. Combination with y_s set to RMS.

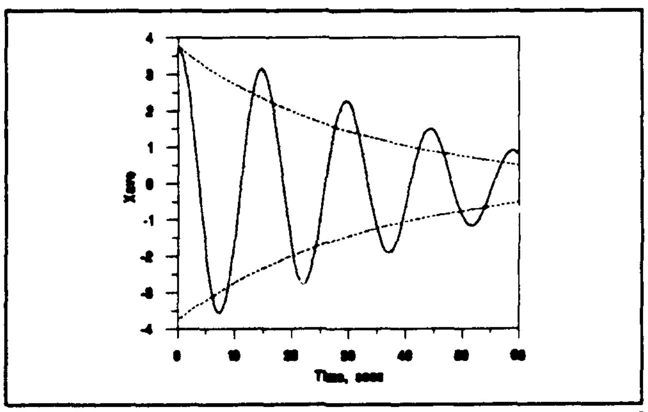

Figure 53. Combination with y_s at 110 percent of RMS.

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